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Prompt acknowledgment of this claim and submission is respectfully requested.

Respectfully submitted,

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Die angehefteten Stücke sind eine richtige und genaue Wiedergabe der ursprünglichen Unterlagen dieser Patentanmeldung.

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HIGHLY DILUTED COMBUSTION FOR GAS TURBINES

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Abstract

The present invention deals with an innovative combustion mode and its implementation into gas turbine combustion chambers. Combustion is carried out in lean conditions at high operating pressure with a very high flue gas recirculation (the ratio flue gas/air being higher than 3). This combustion mode, referred to as flameless combustion, has the potential to reduce the NOx levels built up in the reaction environment thanks to a very unform temperature field and exploiting the positive effect of the flue gas (especially H_2O) on the NOx formation kinetic pathway. A non visible, volume-flame is established, which is expected to successfully address the typical gas turbine problems as flame stability and pulsations.

In the first part of the invention the key features of the flameless combustion are outlined. In the second part several possible embodiments are proposed as how to implement the concept into a gas turbine combustion chamber.

Background of invention

Energy production via fossil fuel combustion presents nowadays two major driving forces for the designer which are paradoxally in contrast to one another:

- The highest achievable effiency (fuel energy saving and CO_2 emissions reduction)
- The lowest achievable pollutant emissions (i.e. NOx)

One of the most used ways to improve efficiency of a combustion process relies upon high combustion air preheating. Combustion takes place at higher flame temperatures and eventually the energy of the high temperature combustion gases is transferred to the combustion air in recuperative or regenerative heat exchangers. A drawback of high air preheat temperatures are increased peak temperatures in the flame with disastrous effect upon the thermal-NOx formation path. Thus the target here evolves into the solution to the conflict of interest between energy savings and NOx-reduction.

A new concept of combustion, applicable to reacting mixture temperatures above the self-ignition treshold, promises to be the potential solution to this dilemma.

The technique has spread over the last decade capturing the interest of many researchers and engineers.

Several investigations have been carried out and are still underway in the field of high temperature processes. The technique has been addressed as flameless combustion, mild combustion, colorless combustion or High Temperature Air Combustion. The common line of all these

different names is the basic concept of a combustion process carried out in a very diluted reacting mixture kept at a temperature above the self-ignition treshold (via a high flue gas recirculation rate).

Flue gas recirculation is used for a twofold goal: dilute the reacting mixture and provide the necessary energy to allow self-ignition.

Exhaust gas recirculation increases the content of inerts of a mixture. Flammability limits for combustion of hydrocarbons and air show that it is possible to obtain flammable mixtures for recirculation rates up to 50%. To provide reliable operating conditions in practical systems, exhaust gas recirculation rates up to 30% are used as a NOx-reducing technique, The recirculation rate R is defined as the ratio between the flow rate of the recirculated flue gas and the flow rate of the fresh mixture fed into the combustion chamber:

$$R = \frac{G_{IR} + G_{ER}}{F + Ox} \tag{1}$$

where:

G_{IR}: Flue gas internally recirculated

G_{ER}: flue gas externally recirculated

F: Fuel

Ox: Fresh oxidant (usually air)

It was recently found that it is possible to stabilize a flame with a much higher flue gas recirculation rate, which produces a non-visible, non-audible flame, due to the very high level of dilution of the reactive mixture. This special condition is achieved when recirculated flue gases are mixed with the reactive mixture prior to reaction; only in this way is a diluted mixture provided before reaction and the technique has an effective impact on NOx formation reduction. The high level of dilution in fact prevents the formation of localized temperature peaks and thus the NOx formation. The aim is to achieve such an operating setup exploting self-ignition of the flammable/diluted mixture, therefore the key issue here is to provide a mixture temperature which is above the autoignition treshold. Such a condition will result in a very low temperature difference between the initial and the adiabatic flame temperature if compared to standard non-diluted flames:

$$T_{ad} = T_{in} - \frac{\Delta H_R}{c_p} \cdot Y_{Fuel} = T_{in} - \frac{\Delta H_R}{c_p} \cdot \frac{1}{R+1} \cdot \frac{F}{F+Ox} \tag{2}$$

$$\Delta T = T_{ad} - T_{in} \propto \frac{1}{R+1} \tag{3}$$

where:

T_{ad} : adiabatic temperature (K)

T_{in} : initial temperature of the reacting mixture (K)

ΔH_R : heat of reaction (kJ/kg)

c_p : specific heat of reacting mixture

Y_{Fuel}: molar fraction of the burned fuel

R : recirculation rate

F : Fuel molar rate

Ox : Oxidant molar rate

Equations 2 and 3 show that the difference between the adiabatic temperature and the initial temperature of the mixture decreases as R increases. The recirculation rate acts on the value of T_{in}, as this is the result of an energy balance between the recirculated flue gas and the fresh oxidant stream fed into the combustion chamber. On the other hand R does not affect the value of the adiabatic temperature as equation 4 shows (from further elaboration of equations 1 and 2, with the hypothesis of adiabatic combustion system):

$$T_{ad} = T_{oxi} - \frac{\Delta H}{c_p} \cdot \varphi(\phi) \tag{4}$$

where:

$$\varphi(\phi) = \phi \cdot \left(\frac{Y_{Fuel}}{Y_{oxi}} \right)_{stoich} + 1 \tag{5}$$

T_{oxi}: oxidant inlet temperature

ϕ: equivalence ration

Y_{oxi}: oxidant mole fraction

The main practical applications of this technique have relied so far on a separate injection method of fuel and air into the combustion chamber, in order to accomplish a two-step mixing process. Fresh air is mixed with recirculated flue gas followed by further mixing with fuel so to reach the targeted thermal conditions of the mixture before ignition takes place. Investigations carried out on this technique report that different flame stability regions are established for different recirculation ratios. The key conclusion was that a stable, diluted, non-polluting flame is achievable for flue gas recirculation rates higher than 300%

This invention depicts several possible solutions to achieve the working conditions necessary to carry out flameless combustion in a gas turbine combustion chamber.

Solutions are proposed as how to achieve the required thermal inlet conditions to assure autoignition of the reacting mixture.
Several injection systems are considered, which do not necessarily limit the working conditions to the recirculation rate threshold of 300%.

Summary of invention

At present the highly diluted combustion technique has been applied to high temperature processes (i.e. steel making industry, glass furnaces).
The object of this invention is to develop an arrangement that allows to carry out this combustion technique into a gas turbine combustion chamber.
The innovation would result in a appealing solution for:

- flame stability problems in modern gas turbine fired with the lean premix concept
- pressure pulsation, noise production
- flashback
- ultra low-NOx emissions (even at very high operating temperatures and pressures)
- operation flessibility on a wide engine load range maintaining high performance levels
- combustion efficiency
- green hause gases reduction

This invention deals with the main issues arising from the idea to apply such combustion concept to a gas turbine combustion chamber.
A wide range of possible operating conditions is considered and several potential solutions are proposed.
The main issues are:

- Combustion air pre-heating
- Flame temperature
- Residence time
- Ignition delay
- Flue gas recirculation rate
- Equivalence ratio
- Flame stability
- Pressure pulsations
- Operating pressure

To run a gas turbine at say 20 bar combustion is carried out in a very diluted flame ($\lambda \geq 2$) where fuel is burnt with air preheated at say 720K by compression. A typical reference value for the flame temperature is

1750K. Ignition delay times are in the order of 3-5ms and the residence time is in the order of 20ms. Targeted emission levels are: UHC and CO below 10ppm and single digit NOx (normalized @15%O_2). These operating conditions refer to a full engine load operation mode.

The implementation of the aforementioned diluted combustion mode to a gas turbine engine should be accomplished in order to improve the engine performance respecting at the same time the aforementioned constraints.

The diluted mode is established once a sufficient amount of flue gas is recirculated into the fresh mixture prior to reaction in a way that the mixture temperature resulting from this dilution is above the self-ignition treshold. One of the main concerns is how to achieve such conditions.

This recirculation can be carried out via an internal or an external flue gas recirculation. Flue gas recirculation can be internally achieved by aerodynamic means (high velocity jets, jet pumps...). The fraction of gas that cannot be further internally recirculated would be externally recirculated by means of pumps and with the use of auxiliary equipment such as heat exchangers and/or compression stages.

Two different kinds of gas external recirculation are possible. In the first solution flue gases are externally recirculated from the end of the combustion chamber back into the primary zone. In the second possible solution flue gases are recirculated from the exit of the turbine expansion stage back to the compressor intake where they mix with the fresh oxidant, in this way the compressor is working as a mixing device. Both solutions are proposed for the concept implementation in the following paragraphs.

The flame temperature could be maintained at the desired operating value with a much lower ΔT as already explained. This would help in suppressing high temperature spots and would bring benefits for uniform temperature field thus affecting performance in terms of emissions and combustion efficiency.

Characteristic time scales would need to be taken into account for implementation into GT combustion. The high dilution of the reacting mixture tends to slow down the kinetics of the process, thus affecting ignition delay times and overall reaction times. This aspect on the other hand has a positive effect on allowing proper mixing to occur prior to ignition and thus avoiding the dangerous formation of localized temperature picks. Due-to the high inlet temperature and thus high process temperature, the reaction, once ignited, takes place in a fairly short time thus not affeting in a negative way the time/space contraints of a gas turbine combustion chamber.

GT combustion is usually run very lean (l≥2), as this proved to be the optimum operating condition to keep the NOx levels at the lowes achievable values. In this condition severe flame stability problems are encountered, since the flame is constantly operated very close to the lean blow out limit. Flameless combustion offers the potential to run the flame richer achieving NOx levels lower than the standard lean premix technique, thus avoiding any stability problem (and most probably an interrelated pressure fluctuation issue). The richer reacting mixture would perform in a better way than the corresponding not diluted flame thanks to the beneficial kinetic effect of the recirculated flue gas. A richer mixture would also be easier to ignite and would thus provide an increased process efficiency. The advantage results even more appealling for reduced load operating conditions, the most difficult to obtain a stable flame with low

emissions. The high initial temperature of the reacting mixture, kept above the self-ignition threshold, would allow to get rid of the diffusion pilot flame, usually needed to stabilize the flame at low loads, causing at the same time increased NOx levels.

The technique has never been applied so far to high pressure systems. The concept has shown actual reduction of the NOx emission levels from atmospheric combustion processes [XXX]. Such reduction has been attributed to the high dilution of the reacting mixture, thus causing a lower oxygen quantity and the absence of localized temperature peaks. At the same time, the positive effect of the recirculated flue gas into the NOx-formation kinetic pathway has been observed.

At high pressure the positive influence of the flue gases into the kinetic pathway (via the N_2O formation-destruction route) is even enhanced thus bringing a significant positive contribution to the emission potential of the process.

The following paragraphs contain an outline of the different proposed solutions for the implementation of flameless combustion into a GT chamber.

Brief description of the drawings

The proposed solutions are depicted in the figures hereafter reported.

Figure 1 represents one of the preferred embodiments. In this case the oxidant compressed at the operating pressure is not further pre-heated. This solution is applicable to cases where the reacting mixture has an initial temperature which is kept above the auto-ignition threshold via the recirculated flue gas without the need for any further heating.

In alternative the reacting mixture might need to be further heated up to reach the auto-ignition threshold. Figures 2 and 3 reports possible configurations where the comburent is heated up via a heat exchanger that exploits the sensible heat of the flue gas from the turbine exit or via a heater that provides heat from an external source, with a positive effect on the efficiency of the simple GT cycle.

Figure 4 depicts a configuration where preheating is performed via a catalytic precombustor. In addition to this, figures 5 and 6 combine a catalytic pre-combustor with a heat exchanger or an external heat source.

In figure 7 flue gas recirculation at high pressure (internal and external to the combustion chamber) is combined with an external recirculation mode where the flue gases are taken from the turbine exit and recompressed with the fresh oxidant.

Finally, figure 8 depicts a solution where any of the aforementioned solutions can be combined with a steam generator system that exploits the heat of the ehxaust gases. While steam is injected into the combustion chamber to further exploit its positive effect on the NOx reduction, the specific power output is boosted as the result of increased flow rate through the turbine stages.

Description of the preferred embodiement

Figure 1 reports the flameless combustion concept embodiement into a gas turbine system. Reported operating conditions are given as an example and refer to a typical full load operation mode.

A compressor C sucks the oxidant 1 from the external environment or any storage location and compresses it to the required operating pressure. The compressed oxidant is then fed (3) into the combustion chamber where combustion with very high level of dilution takes place. Any kind of fuel may be burned with such a combustion technique. The combustion chamber is operated normally with a very high level of flue gas recirculation. Flue gas recirculation may be internal (G_{IR}) or external (G_{ER}) to the combustion chamber. Alternatively, flue gas recirculation rate will be split between an internal flue gas recirculation fraction and an external one to provide a combined flue gas recirculation mode.

Injection of fresh oxidant and fresh fuel into the combustion chamber has to be done in a way that proper mixing among the three streams into consideration (oxidant, fuel and flue gas) is achieved in stages prior to ignition of the mixture. Different solutions can be envisaged and used according to the specific configurations and requirements of the operating system.

A premix injection system can be considered where oxidant and flue gas are well-mixed prior to contact with the fresh fuel, or fresh fuel can be well-premixed with flue gas prior to contact with fresh oxidant. Alternatively a two-stage premix burner can be envisaged where a portion of the flue gas is premixed with the fresh oxidant and the rest is premixed with the fresh fuel and complete mixing of the two mixtures so produced occurs downstream in a second stage mixer.

Another possible solution is that fresh oxidant and fresh fuel are fed via a diffusion type injection system whose aerodynamics are arranged in a way that in the combustion chamber mixing occurs in a way that oxidant and fuel come in touch at the last stage; that is, fresh air or fuel has to come in touch with flue gas prior to contact with fuel or fresh oxidant. The optimum solution will be dictated by space constraints, allowed pressure drops and minimum required residence time.

The high level of flue gas recirculation is normally required to produce a diluted flame, which allows for low emissions. The recirculation rate ($0<R<\infty$) can vary according to the preferred embodiment and, inside the same combustion system, it can be varied during operation to cope with different engine load requirements. The choice of the recirculation rate and its splitting will be dictated by the mixture autoignition threshold, the recirculation systems adopted, the minimum residence time, the allowed pressure drops and mixing capability of the system. When running the system at R=0 a standard, non-diluted, flame type combustion is carried out.

Such combustion systems can be implemented into any of the well-known combustion chambers for gas turbine operation. The combustion chamber may be a can-type, an annular or a can-annular combustion chamber. The choice will be dictated by space constraints, mixing capabilities, emissions potentialities and power output levels.

The stoichiometry of the reacting mixture does not have necessarily to be extremely lean as required for lean premix systems. The equivalence ratio can be adjusted in a way to provide a reacting mixture above the self-ignition temperature whose combustion will satisfy the required turbine inlet temperature at low emissions. In this respect the equivalence ratio of the reacting mixture will be tuned to satisfy such requirements together with the flue gas recirculation rate.

Some oxidant may be by-passed (4) and used as cooling agent upstream the turbine stage, in case it is required (usually 10-25% of total air).

Flue gases (6) so produced together with the cooling stream (4) flow then through the turbine to run it (8). Finally they are discharged (9).

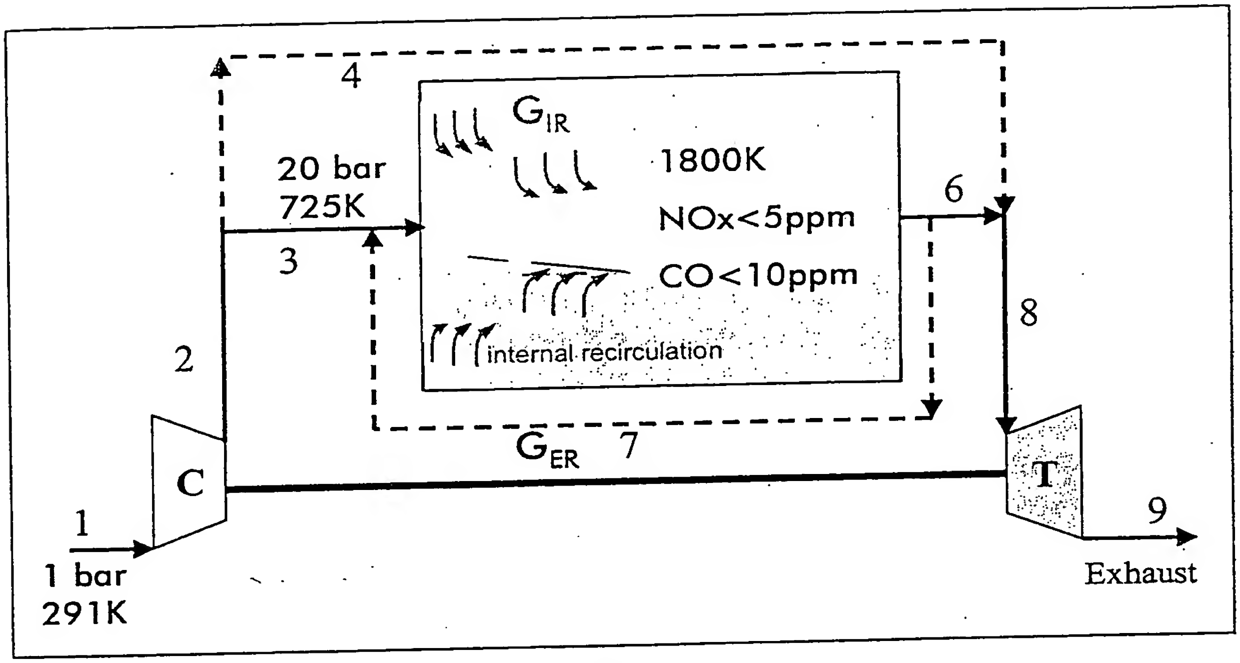

Figure 1

In case the flue gas recirculation rate is not enough to satisfy the targeted thermal conditions of the reacting mixture (i.e. mixture temperature above the autoignition trheshold), an additional oxidant preheating action might be considered (**Fig.2**).

This might be the case during partial load operation when the oxidant is compressed to a lower pressure and has thus a lower temperature at the compressor exit.

As oxidant has been compressed and heated (C) its stream might be split to use a portion for combustion (3) and the other for cooling purpose (4). The oxidant fed into the combustion chamber might be further heated up via a heat exchanger (HX) which uses the residual sensible heat of the flue gases (10) discharged by the turbine (T). The heat exchanger might be a recuperator or a regenerator, according to the most suitable solution for any particular case.

In case the sensible heat of the flue gas from the turbine exit is not high enough to be used for air preheating purposes an external heat source might be used (Q) (Fig.3).

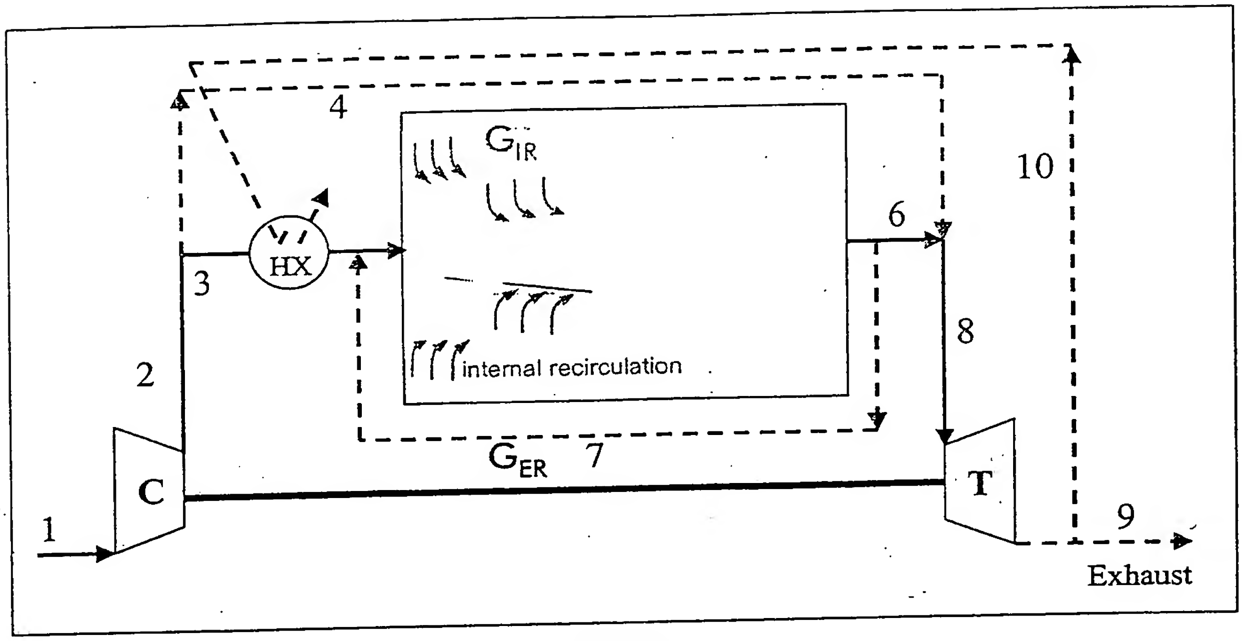

Figure 2

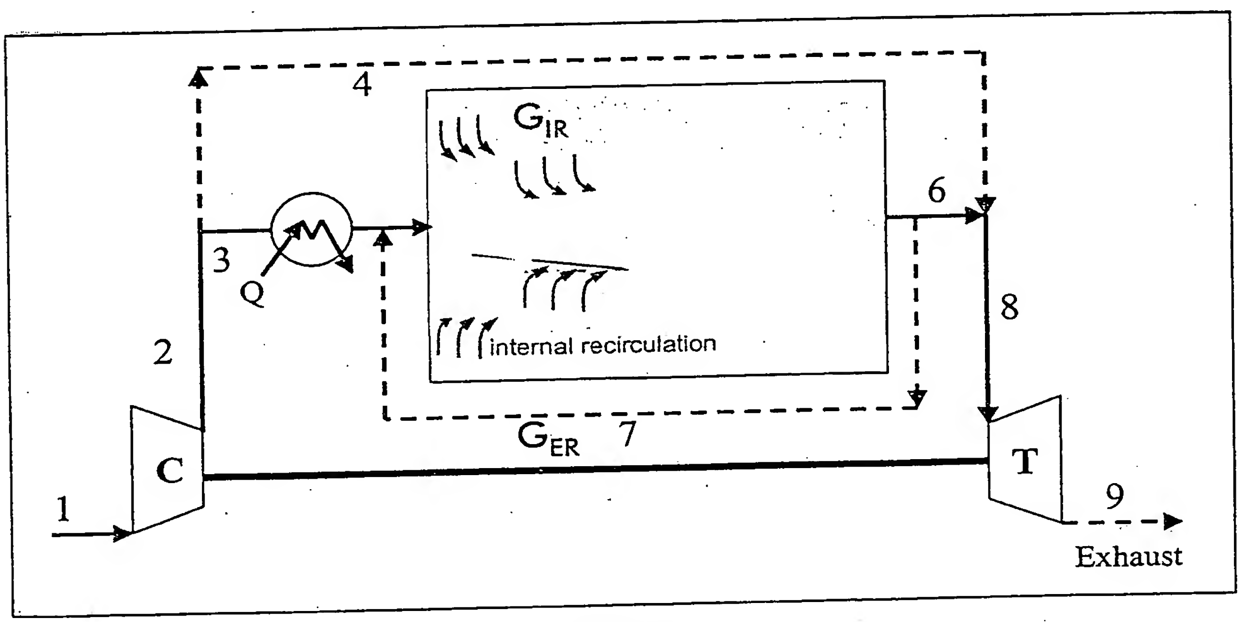

Figure 3

Another way to preheat the comburent to a temperature higher than the compressor exit temperature to satisfy the thermal conditions requirement for the flameless combustion mode is additional heating provided by a catalytic pre-heater or pre-combustor (**Figs. 4-6**).

In **figure 4** one of the possible embodiments with the catalytic pre-burner is depicted, where operating conditions referring to partial load operation mode are reported as an example.

The compressed comburent stream portion used for combustion (3) is mixed with fuel at very lean conditions and flows then through the catalytic preburner in order to enter the combustion chamber downstream at a higher temperature. The catalytic preburner will run at very lean conditions. In this way additional thermal energy will be added to the stream via surface reaction on the catalytic surface without emission. A very lean reacting mixture entering the catalyst will avoid any risk of catalyst deactivation or overheating.

The preheated stream enters the combustion chamber where it mixes with the flue gases internally recirculated and the fuel. Then it ignites burning with a non visible, volume flame. Flue gas at the exit of the combustion chamber can be externally recirculated upstream (8) or downstream (7) the catalytic preburner to provide additional thermal energy and dilution.

The catalytic preburner could be coupled with an additional heater to futrther boost the preheating action. The heater could be a recuperative or regenerative heat exchanger (**Fig.5**) using the residual thermal energy of the flue gases from the turbine exit or energy from an external heat source (**Fig.6**).

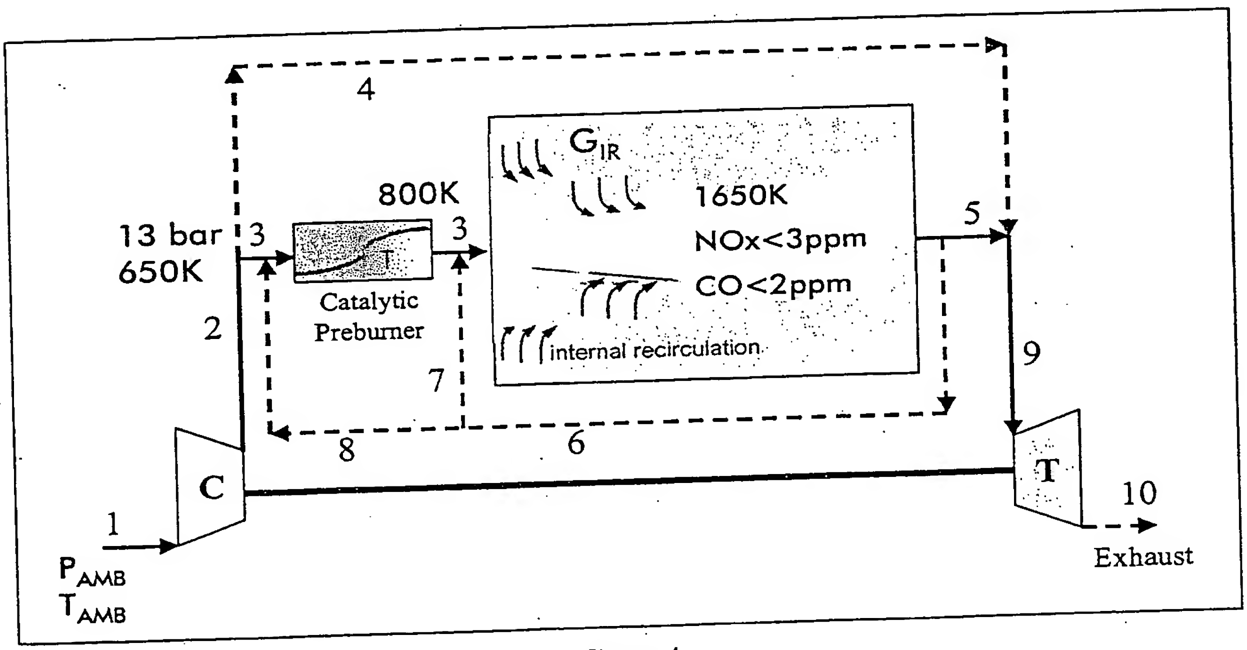

Figure 4

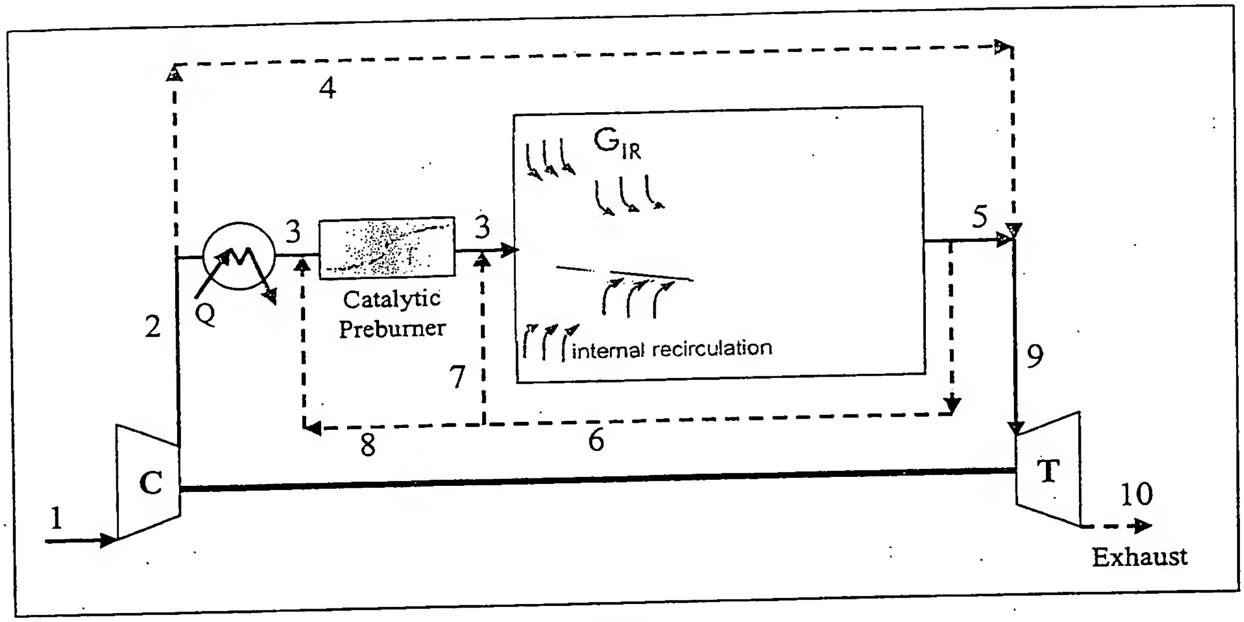

Figure 5

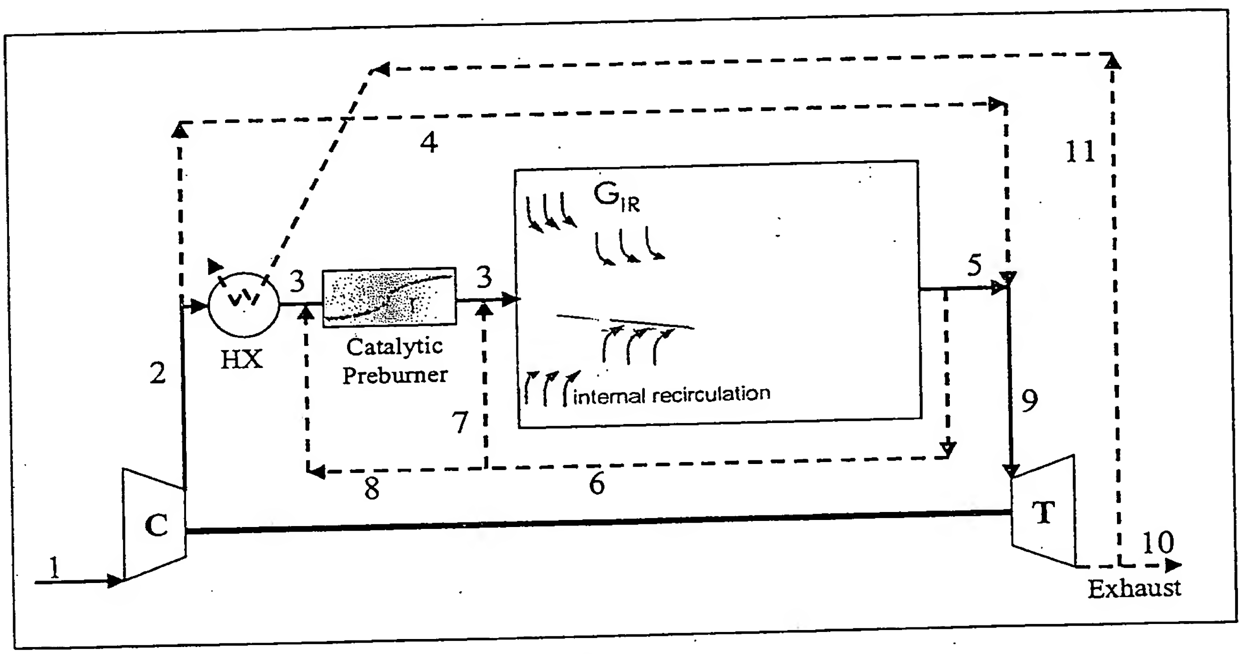

Figure 6

In another embodiment (Fig.7), part of the flue gas can be recirculated downstream the turbine stage (11) by mixing it with the fresh oxidant upstream of the compressor (C). This solution can be pursued when a high flue gas recirculation (for example R>300%) is not entirely achievable internally and an external flue

gas recirculation causes too high-pressure losses. The flue gases are taken from the turbine exit and recirculated to the compressor entrance. Before the compressor entrance they are mixed with the fresh oxidant and the mixture is then compressed before entering the combustion chamber. This alternative flue gas recirculation can be applied in combination with internal and/or external high-pressure flue gas recirculation. The amount of each recirculation rate would depend on several constraints as pressure drop and thermal conditions' requirements to obtain a reacting mixture above the self-ignition threshold inside the combustion chamber. Flue gases will need to be cooled down before mixing with the oxidant stream, as this solution turns to be preferable from an engine efficiency point of view. The heat extracted could be either used to preheat the oxidant before entering the combustion chamber (HX), and/or further cooled down extracting the residual thermal energy to be used by an auxiliary component (Q). This configuration can be applied to all the aforementioned solutions (Figs. 1-6), with preheat of oxidant stream or different utilization of the sensible heat of flue gases.

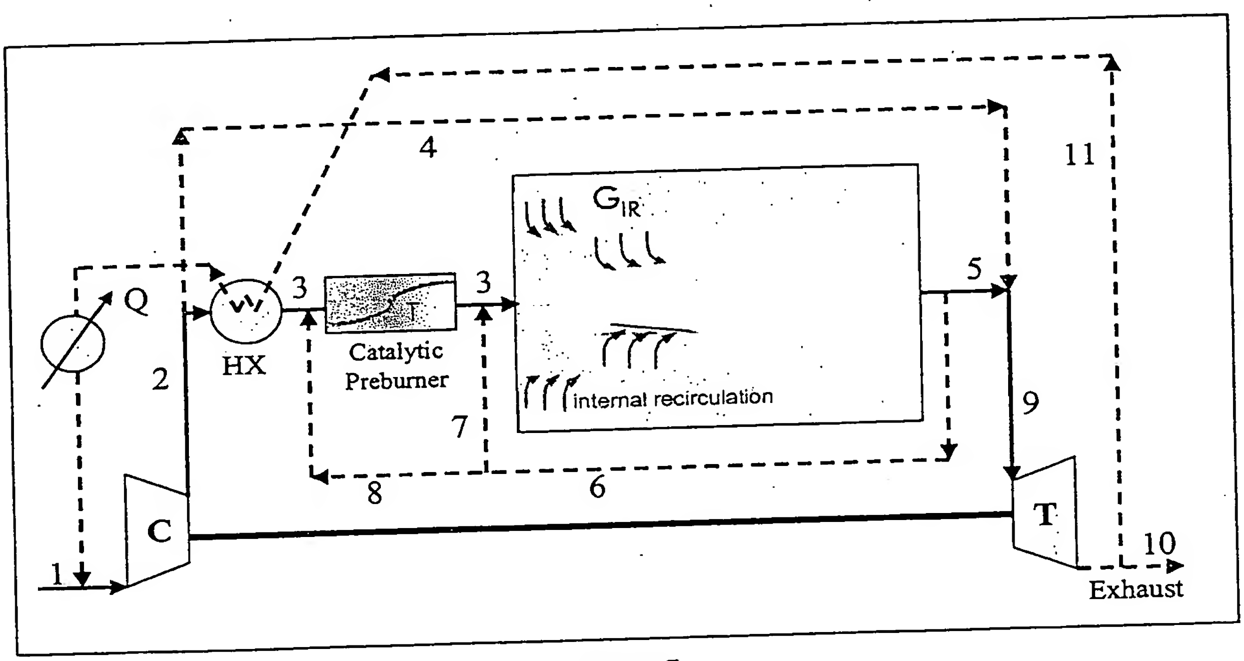

Figure 7

Finally, the flameless combustion mode, as it has been described in the previous embodiements can be coupled with a steam generation process to achieve the so called Steam Injected Gas Turbine (**Fig.8**). In this case the steam injection would result in additional dilution to the already high inert gas fraction due to flue gas recirculation. One could call it a Flameless Steam Injected Gas Turbine (FSIGT).

Steam is produced in a Steam Generator (SG) that uses the energy in the exhaust gas from the gas turbine (9) to produce steam. Steam is then fed into the primary combustion zone (16) to further dilute it and suppress the NOx formation via the N_2O kinetic pathway.

In case steam injection into the combustion chamber does not bring any additional benefit to the diluted combustion performance, then steam can be injected downstream the primary combustion zone to drive the turbine, with a positive effect on the system power output. In a closed loop steam discharged downstream the gas turbine with the exhaus gas can be recuperated in a condenser (C) and further reintegrated into the steam production process (12), while flue gas would be discharged after the condenser stage (11). Alternatively an opena cycle can be used where fresh clean water is continuously fed into the steam generator (14).

An additional advantage of the FSIGT would be an increase in the gas turbine efficiency.

For a given oxidant flow the compressor power demand remains unchanged but the mass flow through the turbine is increased, increasing the power output. The proposed solution would allow to meet ultra low NOx requirements maximizing efficiency.

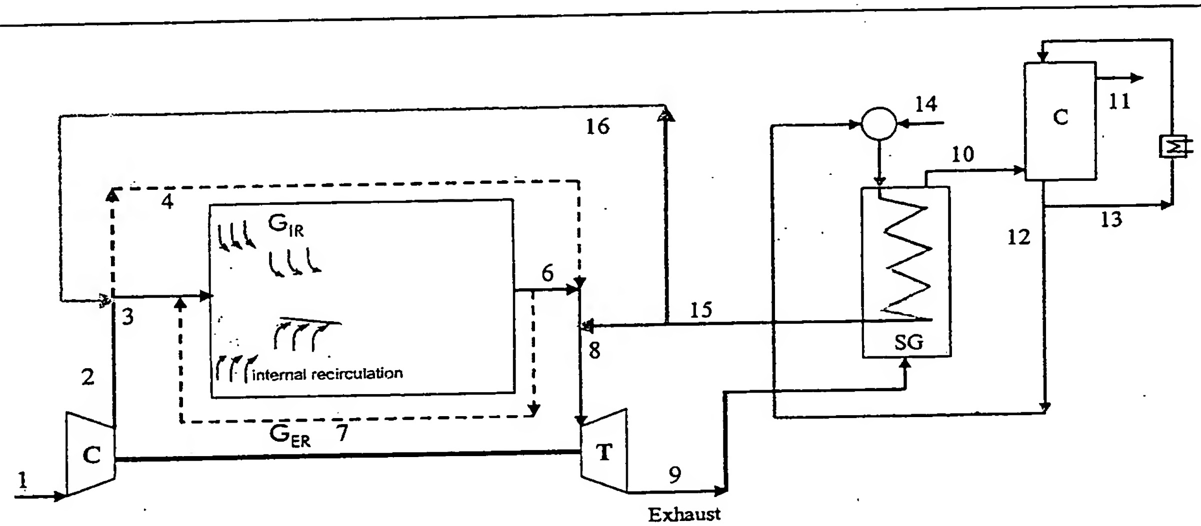

Figure 8

In case an oxygen storage is available or the need to develop a Zero Emission System arises, the described solutions can be easily adapted to use pure oxygen as oxidant and performe a clean combustion in a diluted environment (**Fig.9**). Oxygen would be compressed nd fed into the combustion chamber where a high level of internal (G_{IR}) and/or external(G_{ER}) flue gas recirculation is provided this time to mitigate the explosive effect of the reacting mixture of oxygen and fuel. Combustion takes place without any NOx production, since n2 is abset in the whole process. The flue gas dilution acts as a controller of the flame temperature. The gases produced by the combustion product drive the turbine expansion stage and their energy is further used to produce steam (via the steam generator SG) that can be injected into the combustion system to controll the process temperature (16) and boost the power output (16, 15)

Steam mixes with the combustion products and is the recuperated downstream the steam generator in a condenser (C). The remaining flue gases (mainly CO2) are then cooled down and may be in part recirculated to the compression stage to contribute to the right amount of flue gas dilution necessary to control the combustion process. The CO2 in excess can be removed and stored for sequestration or further use.

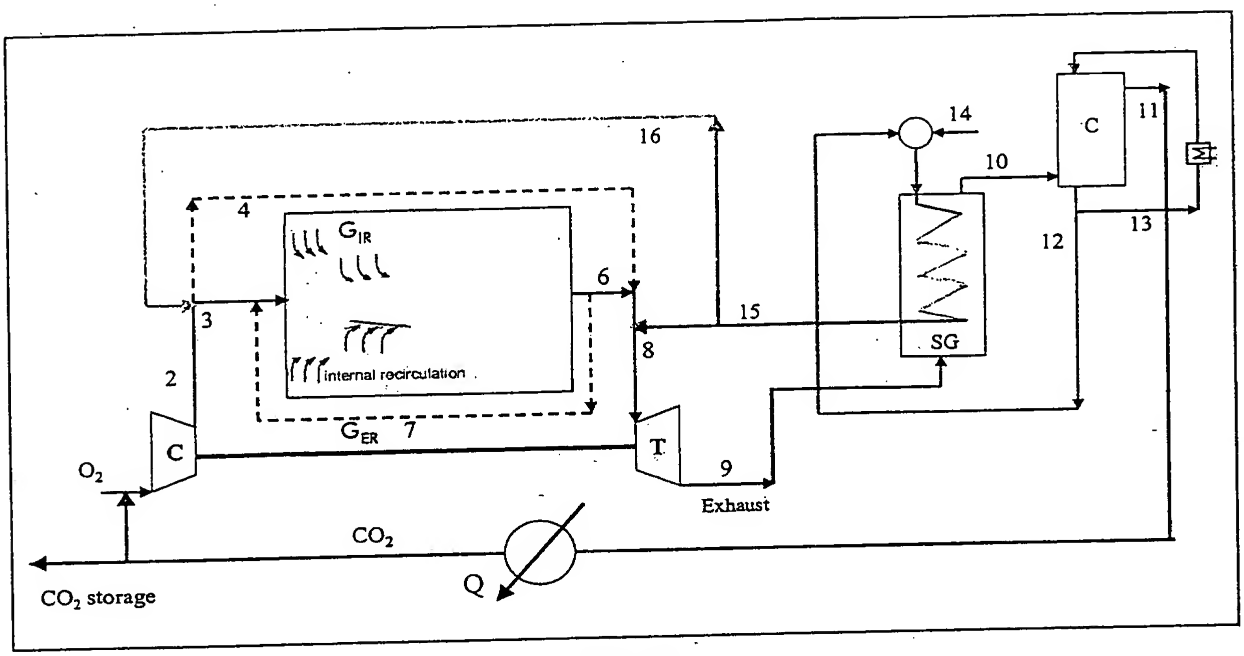

Figure 9